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Vibration of embedded foundation at multi-layered base taking into account non-linear and rheological properties of soils

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Abstract

Calculation scheme of solid multi-layered base of the embedded foundation is offered for description of system vibration "foundation is a multi-layered base". It is shown that in this case consideration of apparent mass of the solid multi-layered base, as well as foundation side surface friction leads to non-periodical (non-harmonic) damped vibration of the foundation. Different contact models including elastic, non-linear and rheological ones with regard to strengthening throughout the time are considered as for calculation for solution of problem of "system" vibration. It is shown that consideration of soil strengthening and side surface friction of the embedded foundation greatly influence the intensity of vibration damping throughout the time.

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Keywords: vibrations, base, soil, rheological properties, nonlinearity.

1. Introduction

It is known that when designing the foundation for machine and equipment with dynamic loads, ground base is considered as a massless and is characterized by stiffness coefficient Kz, Kx and $K\varphi$. Such a simplified model of the base, known as Winkler model, enables us to simplify considerably the solution of differential equations of foundation vibration at compressible base regardless to viscous resistance [1, 4, 5, 12].

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One uses the models which take into account damping properties of the soil, including Kelvin-Voigt model and Maxwell model when it is necessary to account non-elastic resistance of the base [2].

This paper presents the problem of vibration of the embedded foundation at the solid (inertial) multi-layered base taking into account viscous properties of base soils and side surface friction [8, 9].

First attempts to account the apparent mass of base soils are made by E. Reissner, then by O.Ya.Shekhter [11]. One considered the problem of forced vibrations of the round plate at the elastic solid semispace influenced by harmonic disturbing force.

Account of inertial forces of base soils results in the fact that vibration amplitude does not turn into infinity anywhere that is there is no resonance, provided that the increase in Poisson's ratio leads to the increase of energy emission from vibrating foundation to the soil, consequently, the dampting of system vibrations. Besides, account of inertia of base soils results in aperiodic foundation vibration that is there is no vibration motion of the foundation. In this respect, inertial properties of base soils influence more the foundations of low height and large size than the foundations of high height and relatively small base square.

The models with "the apparent mass" are currently used for solution of practical problems with different methods including its setting to the soil volume contained in the "active deformation area" of the base. When calculating wide foundations, dynamic load is considered to be transferred to the ground base as a load-bearing post, conical (trapezoidal) solid mass and semispace.

2. Vibration of embedded massive foundation at the multi-layered solid visco-elastic base

It is known [3, 7] that in case of inertial base, the dynamic equilibrium of the foundation with one degree of freedom under the influence of vibration power can be expressed with the equation:

$$mz'' + kz + \eta z' + F\sin(z') = p_0 \sin(\omega t) \quad (1),$$

where z is a vertical displacement; m is a foundation mass; F is a side surface friction force.

The equation system of type (5) must be solved in case of solid multi-layered base with several degrees of freedom. The number of equations must coincide with the number of degrees of freedom of this system.

Reactive and inertial forces, as well as side surface friction force of foundation and soil appear in case of vibration of the embedded foundation at the soil solid multi-layered base. These forces can considerably influence the character of foundation vibration, including amplitude and vibration frequency, exclude resonance possibility and enable the accumulation of foundation residual settlement and inclination.

The problem of vibration on elastic and inertial uniform base is considered in paper [3] including the approximate calculation scheme where the dynamic load is considered to be transferred to: exclusively load-bearing prismatic soil post; load-bearing solid mass in the form of finite (trapezoidal) solid mass and semispace. One also knows the approximate calculation scheme where base inertia is taken into account by way of joining of active zone soil mass to foundation mass. All these calculation schemes lead to decrease of vibration amplitude and exclude resonance.

This paper offers the approximate calculation scheme of vibration of the embedded foundation at solid multi-layered base with regard to side surface friction of foundation and soil, as well as elastic and viscous soil properties. Soil base is shown as solid layers of finite thickness jointed by elastic and elastic and viscous elements. In this case, each layer with mass m will vibrate individually and, consequently, there will be a system with multiple degree of freedom equal to the number of layers (fig. 1).

Solution of stiffness coefficient of each layer k_i, its mass m_i and mean value of static load p_i, as well as stress distribution angle of statistical load λ are defined for mathematical description of vibration of such a system. The last in the first approximation can be defined on the basis of damping stress coefficient $\alpha(m(z),l/b)$ under the foundation of the central axis z by tables [10] depending on foundation type in plan (rectangle, square, circle). There is dependence between the distribution angle λ and stress damping coefficient $\alpha(2z/b,l/b)$ as follows:

$$\tan\lambda = \frac{b(1-\alpha)}{2\alpha Z_a}, \quad (2)$$

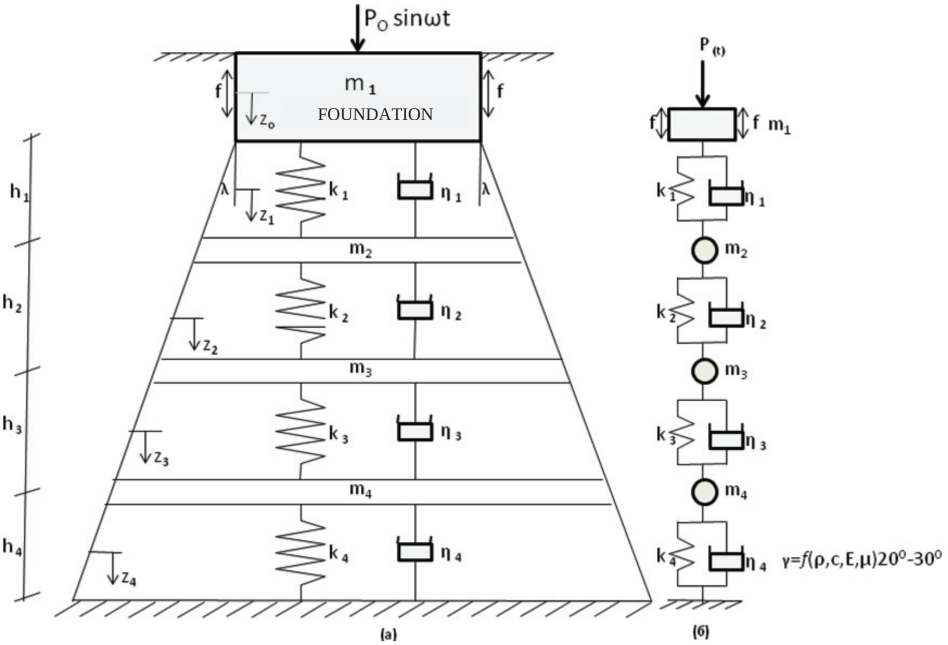

Fig. 1. Calculation (a) and equivalent (б) schemes of vibration of the embedded foundation at multiple solid base

where b and l are the breadth and the length of the rectangular foundation, respectively; Z_a is the lower bound of the compressible foundation thickness defined from the condition σ_{zp}=0,5σ_{zg} [6, 7].

Thus, for example, for rectangular foundation with breadth b = 10m, and length l = 18m at the depth z = 10m, the value makes α = 0.463. Then $tan\lambda$ = 0.58, $\lambda \approx 30°$. Having the λ values, one can define the dimensions of the i-th layer in plan, that is $b_i = b_l + 2\Sigma h_i \cdot tan\lambda$, where h_i is the thickness of the i-th layer. Values p_i and k_i can be defined by formulas:

$$p_i = p_0\left(\frac{b_l}{b_i}\right);\; k_i = \frac{p_i}{S_i};\; S_i = \frac{p_i\beta_i h_i}{E_i}; \tag{3}$$

where E_i is the module of linear deformation of the i-th layer; S_i is of the settlement of the i-th layer;

$$\beta_i = 1 - \frac{2\nu_i^2}{1-\nu_i} \approx 0{,}8. \tag{4}$$

where ν_i is a coefficient of Poisson's ratio of the i-th layer.

Let's consider the simplest situation. Imagine the vibration calculation scheme of the system "foundation is a valuable base" with three degrees of freedom considering that the foundation with mass m_1 co-operates with valuable two-layered base with mass m_2 and m_3, which center of gravity is on one third of the height of layers h_1 and h_2 (fig. 2).

In this case, there is a possibility of only vertical displacement of the foundation. If in the first approximation one does not account energy absorption, then the differential equation of forced vibrations of such a system can be represented as follows:

$$\begin{aligned} &m_1 z_1'' + k_1(z_1 - z_2) + \eta_1(z_1' - z_2') + F\sin(z_1' - z_2') = p_0 \sin(\omega t) \\ &m_2 z_2'' + k_2(z_2 - z_3) - k_1(z_1 - z_2) + \eta_2(z_2' - z_3') - \eta_1(z_1' - z_2') = 0 \ . \\ &m_3 z_3'' + k_3 z_3 - k_2(z_2 - z_3) + \eta_3 z_3' - \eta_2(z_2' - z_3') = 0 \end{aligned} \tag{5}$$

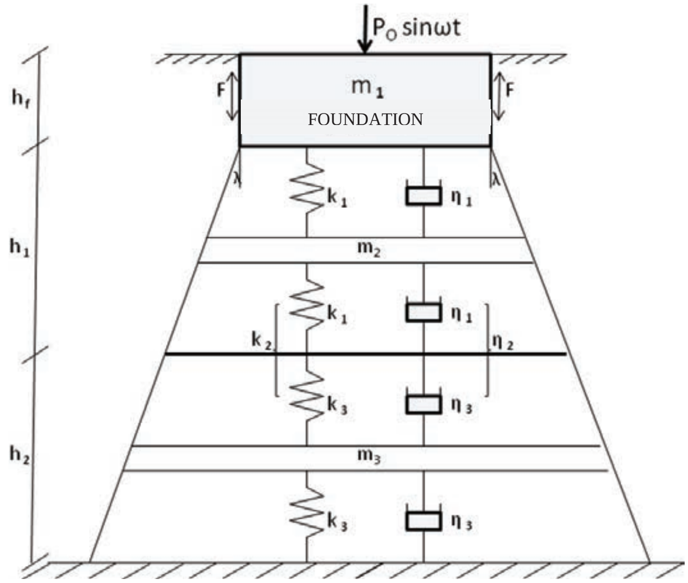

Fig. 2. Vibration calculation scheme of the system “foundation is a valuable two-layered base” with three degrees of freedom

where z_1, z_2, z_3 are vertical displacements of the foundation and centers of gravity of the first and the second layers of the foundation, respectively; m_1, m_2, m_3 are the masses of foundation, the first and the second layers of ground bases, respectively; k_i is a stiffness coefficient of the base, where $1/k_2 = (1/k_1) + (1/k_3)$; η_i is a viscous resistance coefficient of soils, where $1/\eta_2 = (1/\eta_1) + (1/\eta_3)$; F is a side surface friction force of the foundation.

Equation solution (5) can be obtained by numerical method with the help of software MathCAD. The results of the solution are shown in fig. 3 taking into account soil strengthening, that is a $k_i = k \cdot e^{\beta t}$ t , $\eta_i = \eta \cdot e^{\alpha t}$ and at foundation mass m=382 tons, diameter 8 m under influence of disturbing impulse force $P(t)=p_0 sin(\omega t)$, at layer thickness $h_1=h_2$=5m.

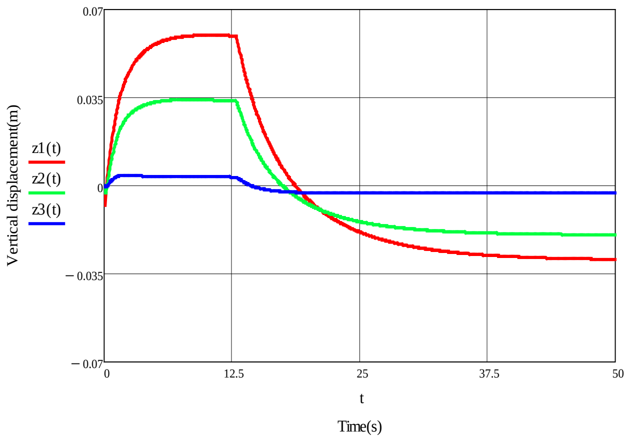

Fig. 3. Curves of vibrations of the system “foundation is a two-layered base” with three layers of freedom plotted based on equation solution (5) with the help of software MathCAD taking into account strengthening and friction of soils by side surface of the embedded foundation; foundation (z_1), first layer (z_2) and second layer (z_3)

It is apparent in case of absence of harmonic vibration and foundation residual settlement. This problem is solved also in elastic approach both in solution (5) and software PLAXIS. Benchmarking of these solutions (figures 4, 5, 6) demonstrates that there is a satisfactory convergence. Consequently, the proposed calculation model (fig. 1) can be used for calculation of vibration system “foundation is a multi-layered valuable base” with the help of software MathCAD.

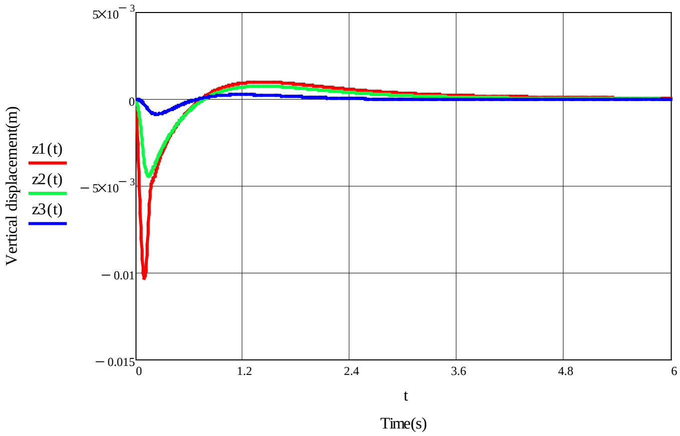

Fig. 4. Curves of vibrations of the system “foundation is a two-layered base” with three layers of freedom plotted based on solution (5) with the help of software MathCAD taking into account the elastic soil model; foundation (z_1), first layer (z_2) and second layer (z_3)

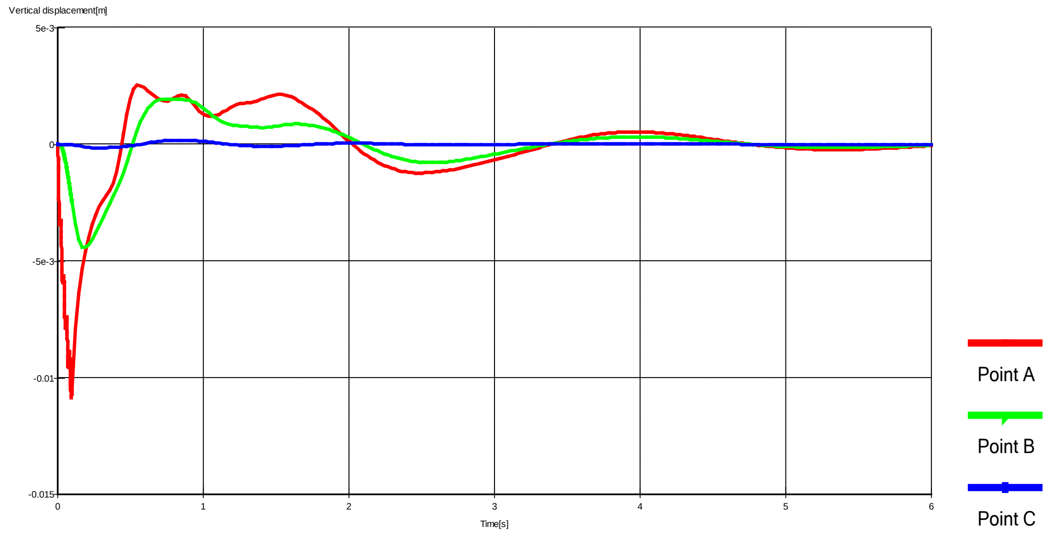

Fig. 5. Curves of vibrations of foundation (Point A), centers of the first (Point B) and the second (Point C) layers of soils taking into account elastic properties of foundation soils plotted based on the results of numerical calculation of plane problem in software PLAXIS

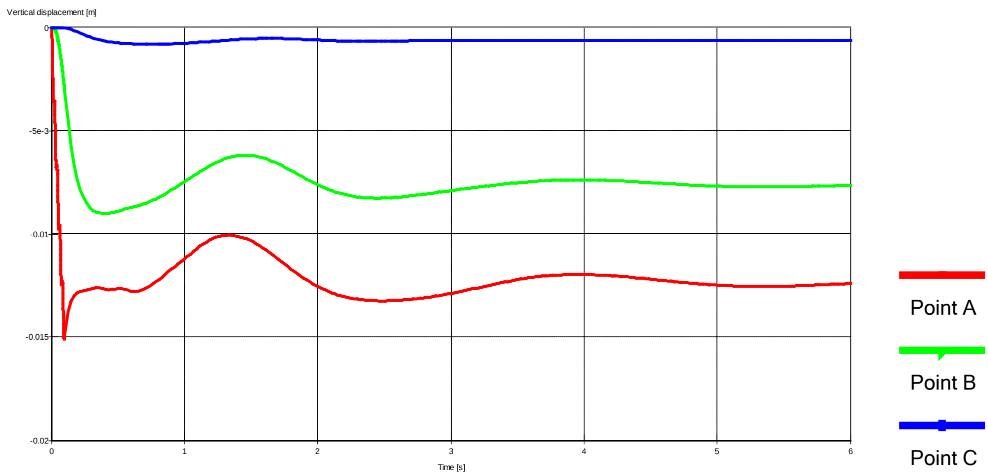

Fig. 6. Curves of vibrations of foundation (Point A), centers of the first (Point B) and the second (Point C) layers taking into account elastic and plastic properties of foundation soils plotted based on the results of numerical calculation of plane problem in software PLAXIS

3. Conclusions

1. The proposed calculation scheme (fig. 1) with adequate accuracy describes the vibration of the embedded foundation at solid multi-layered base.

2. The examples of problems solutions on vibration of the system “foundation is a base” on the ground of the proposed calculation scheme of the solid multi-layered base with several degrees of freedom and their comparison with the results of numerical problem solution in software PLAXIS showed their satisfactory convergence.

3. Account of weight of base soils and side surface friction of the embedded foundation in the proposed model (fig. 1) has considerable influence on the characteristics of foundation vibration including amplitude and accumulation of foundation residual settlement.

Acknowledgements

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